S- X-Band Experiment: Development and Evaluation of a Set of Group Delay Standards

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Group delay standards of 15, 30, and 60 ns have been developed at JPL with advice and consultation from the U.S. National Bureau of Standards (NBS). Calibration data on the delay standards provided by NBS and others are presented and compared. The effects of dispersion and cable reflections are discussed. Calibrations were performed at the S- X-Band Experiment frequencies of 2113, 2295, and 8415 MHz as well as at the nominal range-code modulation frequency of 500 kHz. The standards will be useful for checking out the JPL ranging system accuracy in measuring delay changes of about 15 to 60 ns.

I. Introduction

In 1969, Sokov and Semenova (Ref. 1) proposed a unified system within the USSR for checking group time delay measuring instruments manufactured there. This system was based upon primary group delay standards and working standards consisting of lengths of coaxial cable for small values of delay and helical cables or ultrasonic delay lines for large values of delay in the range of 1 to 10^4 μs.

There has been no corresponding system proposed in the USA, but a set of group delay standards having delays in the range of 15 to 60 ns have been designed at JPL with advice and consultation from the U.S. National Bureau of Standards (NBS).

The need for such standards arose at JPL in 1971 for checking the accuracy and precision of the range calibration system installed at a Deep Space Station at Goldstone, California. The system was used in 1973 for the S- X-Band Experiment (Ref. 2) which involved the measurement of differences in the time delays of signals at S- and X-band frequencies (2295 and 8415 MHz) being transmitted from the Mariner 10 spacecraft while in its interplanetary flight to Venus and Mercury.

For the S- X-Band Experiment, it was required that the range measurement system be checked for its accuracy in

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the measurement of small, as well as large, changes of time delay. For verifying small delay change measurement accuracy, the development of delay standards was required. It was desirable that a standard delay of about 30 ns be known to within ±0.1 ns, if possible.

After consultation with NBS personnel, JPL wrote specifications and procured three special lengths of cable from the Phelps Dodge Company. These cable lengths had nominal delays of 15, 30, and 60 ns, respectively. In the following, the cables are described and measurements by NBS and others are reported. The uncertainties in the measurements are discussed, and the degree of confidence obtained in the standard delay cables is assessed.

II. Description of Delay Standards

In order to operate at frequencies up through 8415 MHz without higher mode propagation, and with minimum leakage, the outer conductor of each cable was specified to have an inner diameter of 8.255 mm (0.325 inch), a characteristic impedance of 50 ohms, a solid aluminum outer conductor, and a foam polyethylene dielectric having a nominal permittivity of 1.50. The inner conductor had an outer diameter of 2.972 mm (0.117 inch). The phase-temperature coefficient of this type of cable is about −28 parts per million per °C (−15.6 parts per million per °F) over the temperature range of −46°C (−50°F) to 38°C (100°F) (Ref. 3).

Each cable has Type N male and female connectors conforming to MIL-C-39012. The cables were coiled and potted as shown in Fig. 1, and had the connectors arranged for convenient insertion into a measurement system. Near each cable end there is a transition from the 7-mm 50-ohm line size of the connectors to the cable diameters given above. The transitions plus connectors give rise to small reflections.

The voltage reflection coefficients and characteristic insertion losses or attenuations of the cables at some specific test frequencies are given in Table 1. The effects of reflections and cable attenuations on delays have been analyzed by the authors in another paper (Ref. 4). It was found that cyclical variations of delay with frequency due to reflections will decrease in amplitude as the cable attenuation increases. Thus, even though the reflection coefficients in Table 1 increased with frequency, a corresponding increase in attenuation kept the variation in delay quite low.

III. Measurement Methods

In the JPL range measurement system for the S- X-Band Experiment, the envelope delays of a square wave (at approximately 500 kHz) modulating S- and X-band carriers are determined. Thus, the quantity of interest in the standard delay cables is the envelope delay or group delay τ_g. In the case of no distortion of the envelope, these are the same, and proportional to the rate of change of phase shift ϕ with frequency f (Ref. 5). This relationship is as follows:

$$\tau_g = [-1/(2\pi)](d\phi/df) \tag{1}$$

where τ_g is in seconds, ϕ is in radians, and f is in hertz. If a phase change $\Delta\phi$ is measured over a frequency interval Δf, then

$$\tau_g \cong [-1/(2\pi)](\Delta\phi/\Delta f) \tag{2}$$

If significant distortion is present, the concept of envelope delay lacks uniqueness and loses significance. The cables were designed to have low dispersion, and measurements of envelope delay and group delay were expected to agree closely.

Several different measurement techniques were employed and measurements were made by JPL, Western Automatic Test Services (WATS), and NBS. The various measurement methods used at each laboratory are listed in Table 2.

In the case of Method 1, a number of impedance measurements were made with Twin-T and Maxwell Bridges at 400, 500, and 600 kHz, and the slopes of the phase shift versus frequency characteristics were calculated at 450 and 550 kHz and averaged to obtain the values given in Table 3. These data were previously reported in Refs. 6 and 7.

In the case of Method 2a, the insertion phase shift of each cable was measured in a phase bridge system tuned to have low reflections at the insertion point at frequencies near the desired frequencies. Group delay was calculated from Eq. (2) and the frequency interval Δf over which the data were taken was 2 MHz (Ref. 6).

In the case of Method 2b, the automatic network analyzer was programmed to read out the group delay as calculated from the change in the insertion phase shift between closely spaced frequencies (10 or 15 MHz) near the desired test frequencies. The frequency interval used to calculate group delay from Eq. (2) was 30 MHz for most of the test results to be presented for this method.

In the case of Method 3a, the delays between corresponding maxima on RF bursts (obtained by gating the output of a microwave source) at two points in the system were measured on an X-Y recording of the outputs from a sampling oscilloscope. The gating signal was obtained from a countdown circuit and derived from the microwave signal. For the triangular modulation pulse used, most of the RF energy was contained in a bandwidth of about 400 MHz for test results at 2113 and 2295 MHz, and about 1300 MHz for test results at 8415 MHz (Ref. 6).

A block diagram of the test setup for Method 3b may be seen in Fig. 2. A baseband pulse of 1000-ns width was used to modulate the microwave signal at 2295 MHz. The delay was measured before and after insertion of the cable by means of a computing counter having a resolution of 0.1 ns (Ref. 8). Data were not obtained at 2113 MHz or 8415 MHz due to difficulty in obtaining low reflection coefficients at the insertion point with system components that were available in the laboratory.

In Method 4, the JPL Mu-ranging system (Refs. 9 and 10) generates a range code of approximately 500 kHz, which phase modulates an uplink RF carrier of 2113 MHz. The ground station transmits this modulated carrier to a target transponder for retransmission back to the ground station at coherent downlink frequencies of 2295 and 8415 MHz. The ground station receiver extracts the range-code modulation, and the ranging system measures the phase difference between the transmitted and received range codes by use of correlation techniques. The measured phase shifts enable determination of round-trip propagation delays. The total system delays were measured before and after insertion of the delay standards at different points in the ground station S- or X-band ranging paths. Additional details of the particular JPL Mu-ranging system, receiver subsystems, and test setup that were used may be found in Ref. 11.

IV. Results

A summary of the measured results are given in Table 3. The values shown for each method represent an averaging and condensation of more extensive data. To enable comparisons of the various methods, a weighted overall average was obtained at each test frequency for each of the delay standards. The weighted averages were obtained in a straightforward manner using weighting factors inversely proportional to the square of the estimated limits of uncertainty for each measurement method. The estimated error limits as well as deviations from the weighted average are shown in Table 4.

Examination of the data in Table 4 shows that the discrepancies between the measured results and the weighted averages are nearly all within the estimated limits of error. The main examples where this is not true are in Method 3a for the 30-ns cable at 2113 MHz (0.13 versus ±0.08 ns) and 2295 MHz (0.14 versus ±0.08 ns). The lack of agreement is within 0.06 ns, and this could be due to failure to include errors due to reflection interactions in the estimated limits of uncertainty. As will be discussed later, the effect of reflections from discontinuities at the cable ends should be considered in estimating the error limits of each of the measurements, since this effect is significant compared with other sources of error. This was not done for any of the measurement methods because the results of the analysis of Ref. 4 were not known at the time the measurements were made.

In Table 4 the estimated error limits for the JPL ranging system (Method 4) are not shown, and the Method 4 results were not included in obtaining the weighted averages shown in Table 3. The reason for this is that the magnitudes of various errors for this measurement method were not sufficiently well known. After the measurements reported in this article were made, it was found that the ranging system measurement error is a function of waveform distortions and total system delay (Ref. 10) and also of changes in received signal levels. The calibration data required to refine the results were not later retrievable, and it was not feasible to repeat the measurements.

The JPL ranging system is presently not capable of subnanosecond-type accuracy, since it was designed primarily to enable accurate measurements of large time delays of weak signals (such as would be received from a distant spacecraft) in the presence of noise. The results from this system (Method 4) were presented mainly to illustrate the usefulness of group delay standards for testing small delay change measurement accuracy of an actual operational system for measuring time delay.

V. Discussion of Error Sources

A. Dispersion

Dispersion is an important consideration in the JPL ranging system measurements because it is necessary to avoid distortion of the square wave envelope to keep errors in delay measurements from this source small. For example, if one needs to consider 11 harmonic components of the 500-kHz square wave to accurately represent a square wave for purposes of delay measurement, then sidebands ±5.5 MHz of 2113, 2295, and 8415 MHz must be free of distortion due to dispersion.

Figures 3, 4, and 5, respectively, show the results of measurements obtained with an automatic network analyzer at frequencies from 2000 to 2500 MHz, 5825 to 6775 MHz, and 8000 to 9000 MHz. The data in these figures show that at these microwave frequencies the group delays are essentially constant with frequency to within ±0.1 ns. Therefore, the effects of dispersion in the standard cables would be insignificant for a square wave modulated carrier at 2113, 2295, and 8415 MHz.

Dispersion effects near 500 kHz are also of considerable interest because the delay standards will be inserted into the baseband ranging path as well as into the intermediate frequency (IF) and radio frequency (RF) portions of the JPL ranging system to help determine the location of error sources. To determine whether or not significant dispersion effects were near 500 kHz, data were obtained at 400, 500, and 600 kHz using Method 1.

The results in Table 5 at 400, 500, and 600 kHz (Ref. 7) show that a small, but significant, dispersion effect is present at these frequencies. The dispersion is due to changes in skin effect in the conductors. It has been noted (Ref. 12) that at frequencies below, say, 10 MHz, a decrease in frequency produces a significant increase in the inductance per unit length without greatly affecting the capacitance, such that the (phase) velocity of propagation decreases. At higher frequencies, the skin depth remains small compared with the cross-sectional dimensions of the cable, and changes in skin depth do not produce significant dispersion effects. This is borne out by the data shown in Figs. 3–5 at microwave frequencies.

B. Internal Reflections

The effect of reflections upon the variation with frequency of group delays of standard cables can be assessed with reference to the data in Table 1 and the analysis and graph of Ref. 4. These effects are small (less than 0.3 ns) for the conditions usually encountered here, but in developing confidence in the standards and the measured results, it is necessary to show this.

Reflections at the ends of the cable will interact, going in and out of phase as the frequency changes, and produce cyclical changes in the group delay. The magnitude of the effect depends upon the magnitudes of the reflections and the attenuation of the cable. The reflections can be due to system mismatches, discontinuities of connector pairs where the cables are connected into the system, and discontinuities between the cables and the connectors due to changes in conductor diameters. At the insertion point, it is possible to tune the measurement system to reduce mismatches or to use isolators and connectors having low reflections. Then any residual reflection interactions will be due primarily to discontinuities internal to the cable.

Figure 6 shows the type of variation obtained where large discontinuities were placed at the ends of a 30-ns coaxial cable. The cyclical variations in group delay were purposely made large to illustrate the effect. It is clear that the group delay varies with frequency about an average value near 30 ns. The cyclical variation due to reflections from discontinuities at the ends of the cable has a period of about $1/(2\tau_p)$, where τ_p is the nominal phase delay of the cable, and for a low dispersion cable τ_p may be replaced by τ_g. In Fig. 6, it can be seen that for the 30-ns delay standard, a full period of cyclical variation occurs in a frequency interval of 16.7 MHz.

If one measures the group delay of a 30-ns standard by measuring phase shifts at the ends of a large frequency interval (large enough to encompass several cycles of the cyclical variation which occurs in phase shift as well as in group delay), one will obtain a value of group delay close to the average value of 30 ns. However, if one uses the same method with a frequency interval much smaller than a period of the cyclical variation, one will obtain a value of group delay which lies somewhere on the cyclically varying curve of Fig. 6.

When the cable reflection coefficients are reduced to the values shown in Table 1, from 0.02 to 0.07, it can be demonstrated that the cyclical changes in group delay with frequency are small for the standard cables. Suppose we assume that the input reflection coefficient of 0.07 shown in Table 1 is the result of discontinuities at each end of the 30-ns cable having reflection coefficients of 0.05. This is a reasonable assumption since the wave reflected from the opposite end discontinuity is attenuated by the cable loss but can combine in phase with the wave reflected from the discontinuity at the input side. Applying this reflection coefficient of 0.05 and an attenuation of 4.13 dB (at 8415 MHz) in the graph (Fig. 5 of Ref. 4), the cyclical variation of group delay with frequency is found to be (30/100)(±0.19) = ±0.06 ns. Although the amplitude of this delay variation is very small compared with the nominal delay of 30 ns, it is significant when compared with the limits of uncertainties of the various measurement methods shown in Table 4.

VI. Conclusions

The results show that the standard cables are suitable for the intended application, and that the different measurement methods of independent laboratories generally agree within estimated limits of error. Two of the major sources of errors that can cause discrepancies between various measurement methods have been investigated. These error sources are dispersion and internal reflections.

It was found that although significant dispersion was observed at frequencies near 500 kHz, there was no significant effect observed at tested microwave frequency bands between 2000 to 9000 MHz. These results indicate that the most accurate measurements of group delay can probably be made by measuring phase shift variation with frequency using a fairly wide frequency interval, say, 100 MHz or so, provided the phase shift varies linearly with frequency over that range. This was substantially the case for the standard delay cables at the microwave frequencies.

Cyclical variations of phase can occur as a function of frequency due to reflections from small discontinuities at the ends of the cables where dimensional changes occur going into the connectors. These phase deviations from linearity give rise to small cyclical variations of group delay with frequency. If the cyclical variation in group delay has an amplitude that is negligible compared with the error limit in measurement, then one should use a wide frequency interval so as to obtain an accurate value for the average group delay. However, if the cyclical variation in group delay has an amplitude that is larger than the error limit in measurement, then a small frequency interval should be used in order to measure the amount the group delay is above or below the average value at the particular frequency of interest.

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References

1. Sokov, I. A., and Semenova, V. P., "Measurement of the Group Time Delay and Checking on Group Time Delay Measurement Devices," *Measurement Techniques*, Vol. 14, No. 9, Sept. 1971, pp. 1387–1390. Translated from Izmeritel'naya Tekhnika, No. 9, pp. 63–65, Sept. 1971. Original article submitted Nov. 27, 1969.

2. Levy, G., Dickinson, R., and Stelzried, C., "RF Techniques Research: S/X-Band Experiment," JPL Space Programs Summary 37-61, Vol. III, pp. 93–95, Feb. 20, 1970.

3. Meola, W., "Phase-Temperature Coefficient of Phelps Dodge FXA 38-50 Semirigid Cable," Engineering Report 162, Phelps Dodge, North Haven, Connecticut, Jan. 9, 1970.

4. Beatty, R. W., and Otoshi, T. Y., "Effect of Discontinuities on the Group Delay of a Microwave Transmission Line," *IEEE Trans. Microwave Theory Tech.*, Vol. MTT-23, No. 11, pp. 919–923, November 1975.

5. *IRE Dictionary of Electronics Terms and Symbols*, Inst. of Radio Engineers, N.Y., 1961. See p. 53, Envelope Delay; p. 104, Phase Delay.

6. Roe, K. C., *Delay Line Measurements*, NBSIR 73-332, National Bureau of Standards, Boulder, CO, August 3, 1973, 10 pages.

7. Estin, A. J., and Jones, R. N., private correspondence (additional test data from National Bureau of Standards, Boulder Laboratories, were given in letter dated May 13, 1975).

8. Gordon, G. B., and Reeser, G. A., "Introducing the Computing Counter," *Hewlett-Packard Journal*, Vol. 20, No. 9, pp. 2–8, May 1969.

9. Martin, W. L., and Goldstein, R. M., "Binary Coded Sequential Acquisition Ranging System," U.S. Patent 3,659,292, April 25, 1972.

10. Martin, W. L., "System Performance of the Dual-Channel Mu-II Sequential Ranging," *The Deep Space Network Progress Report 42-26*, pp. 54–68, April 15, 1975.

11. Otoshi, T. Y., ed., *A Collection of Articles on S/X-Band Experiment Zero Delay Ranging Tests*, Tech. Memorandum 33-747, Vol. I, Jet Propulsion Laboratory, Pasadena, CA, pp. 23–32, November 1, 1975.

12. Anderson, A. R., and McCraven, M. R., *Changes in Coaxial Cable Delay with Temperature and Frequency*, Engineering Report No. E-131, Phelps Dodge, North Haven, Connecticut, May 31, 1967.

Table 1. Measured voltage reflection and loss characteristics of group delay standards

Nominal delay of standard cable	Input voltage reflection coefficient magnitude			Characteristic insertion loss, dB		
	2113 MHz	2295 MHz	8415 MHz	2113 MHz	2295 MHz	8415 MHz
15 ns	0.02 (M)[a] 0.02 (F)[b]	0.02 (M) 0.02 (F)	0.06 (M) 0.05 (F)	0.82	0.87	2.04
30 ns	0.01 (M) 0.01 (F)	0.02 (M) 0.02 (F)	0.06 (M) 0.07 (F)	1.63	1.75	4.13
60 ns	0.02 (M) 0.02 (F)	0.03 (M) 0.02 (F)	0.05 (M) 0.07 (F)	3.29	3.49	8.26

[a]Denotes male connector input side.
[b]Denotes female connector input side.

Table 2. List of measurement methods and laboratories

Method	Laboratory	Description of method
1	NBS	Measure open- and short-circuit impedances at 400, 500, and 600 kHz, and calculate phase constants of cables. Then group delay is calculated from the range of change of phase shift with frequency.
2a	NBS	Measure phase shift versus frequency at frequencies near 2113, 2295, and 8415 MHz using phase bridge.
2b	WATS	Measure rate of change of phase shift with frequency with HP 8542A automatic network analyzer system at frequencies near 2113, 2295, and 8415 MHz.
3a	NBS	Measure time delay between corresponding peaks of an RF pulse burst at frequencies near 2113, 2295, and 8415 MHz.
3b	JPL	Measure time delay of a baseband pulse at a repetition rate of 500 kHz, using an HP 5360A computing counter. The baseband pulse modulates the microwave frequency of 2295 MHz.
4	JPL	Measure the phase shift of a 500-kHz modulating envelope on RF carrier frequencies of 2113, 2295, and 8415 MHz using the JPL Mu-ranging system.

Table 3. Summary of measured group delays in nanoseconds

Frequency	Laboratory	Method (see Table 2)	Nominal group delay of cable		
			15 ns	30 ns	60 ns
500 kHz	NBS	1	15.20	30.34	60.88
2113 MHz	NBS	2a	15.09	30.01	59.94
	NBS	3a	14.95	30.18	60.07
	WATS	2b	15.04	29.98	59.97
	JPL	4	16.51[a]	31.28[a]	61.11[a]
	Weighted average		15.00	30.05	59.98
2295 MHz	NBS	2a	15.09	29.96	59.98
	NBS	3a	15.04	30.21	59.82
	WATS	2b	14.98	30.02	59.99
	JPL	3b	15.01	30.03	60.08
	JPL	4	16.51[a]	31.28[a]	61.11[a]
	Weighted average		15.02	30.07	59.97
8415 MHz	NBS	2a	15.10	30.12	60.03
	NBS	3a	15.03	29.90	59.91
	WATS	2b	15.03	30.03	60.08
	JPL	4	—	29.84	57.67
	Weighted average		15.03	30.03	60.06

[a]A cable standard was inserted into a common transmit/receive signal path of the JPL ranging system. This insertion caused the total measured delay change to be the sum of the cable delay at 2113 and 2295 MHz. It was not possible to determine the cable delay at the individual frequencies from these data. However, since the two frequencies were reasonably close together, it was assumed that the delay at each frequency was the same and therefore equal to the total measured delay change divided by 2.

Table 4. Deviations from average and estimated limits of uncertainty

Frequency, MHz	Laboratory	Method	Nominal group delay of cable					
			15 ns		30 ns		60 ns	
			Dev. from avg., ns	Est. error limit, ns	Dev. from avg., ns	Est. error limit, ns	Dev. from avg., ns	Est. error limit, ns
2113	NBS	2a	0.09	±0.13	−0.04	±0.13	−0.04	±0.13
	NBS	3a	−0.05	±0.05	0.13	±0.08	0.09	±0.14
	WATS	2b	0.04	±0.06	−0.07	±0.06	−0.01	±0.06
	JPL	4	1.51	—	1.23	—	1.13	—
2295	NBS	2a	0.07	±0.13	−0.11	±0.13	0.01	±0.13
	NBS	3a	0.02	±0.05	0.14	±0.08	−0.15	±0.14
	WATS	2b	−0.04	±0.06	−0.05	±0.06	0.02	±0.06
	JPL	3b	−0.01	±0.30	−0.04	±0.30	0.11	±0.30
	JPL	4	1.49	—	1.21	—	1.14	—
8415	NBS	2a	0.07	±0.13	0.09	±0.13	−0.03	±0.13
	NBS	3a	0.00	±0.05	−0.13	±0.13	−0.15	±0.27
	WATS	2b	0.00	±0.04	0.00	±0.04	0.02	±0.06
	JPL	4	—	—	−0.19	—	−2.39	—

Table 5. Measured phase and group delay of standard cables at frequencies near 500 kHz (Method 1)

Frequency, kHz	Nominal delay in nanoseconds of standard cable		
	15	30	60
	Phase delay in ns		
400	15.44	30.85	61.70
500	15.39	30.75	61.52
600	15.36	30.68	61.43
	Group delay in ns		
450	15.18	30.35	60.77
500	15.20	30.34	60.88
550	15.23	30.33	60.99

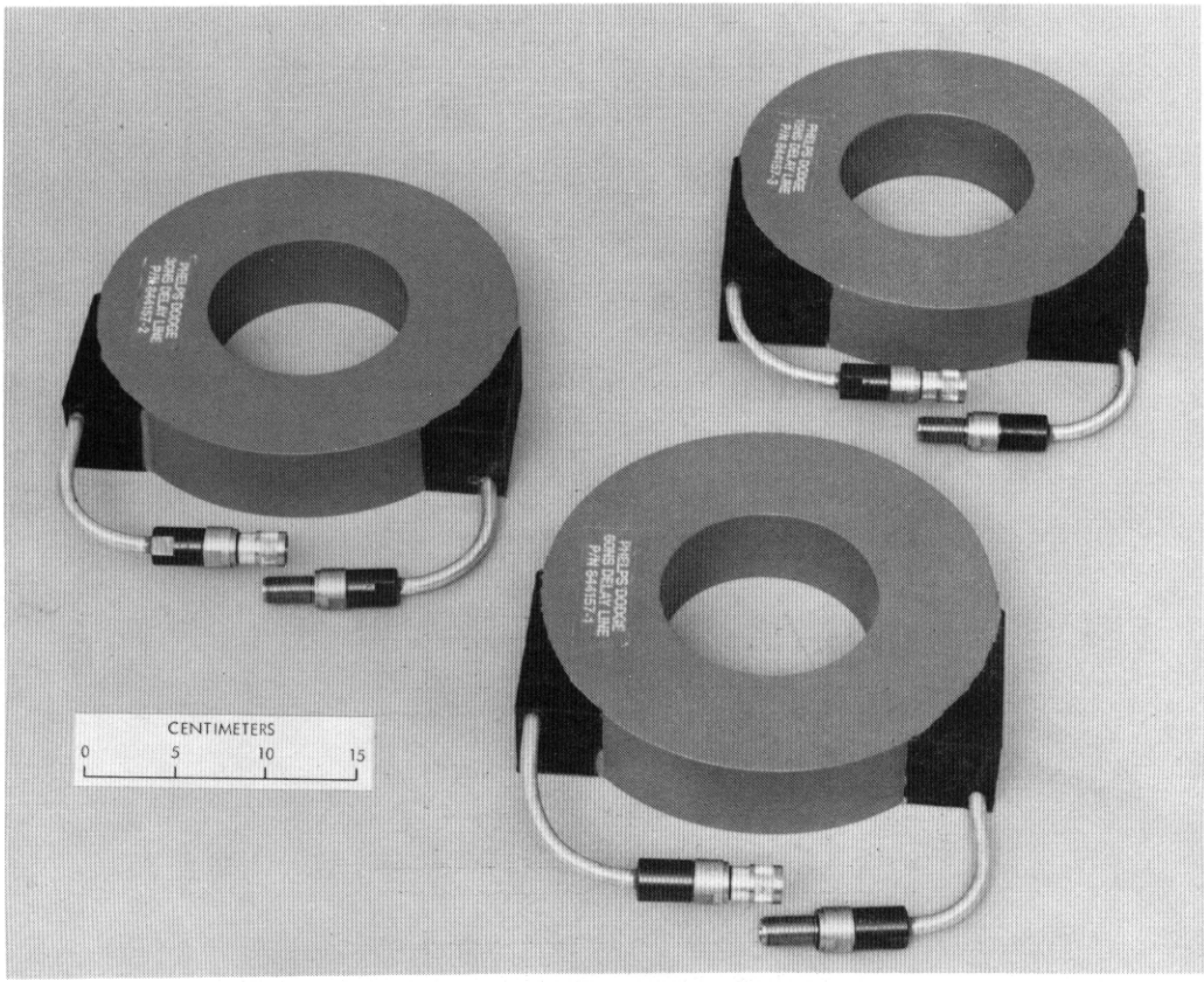

Fig. 1. Group delay standards of 15, 30, and 60 ns

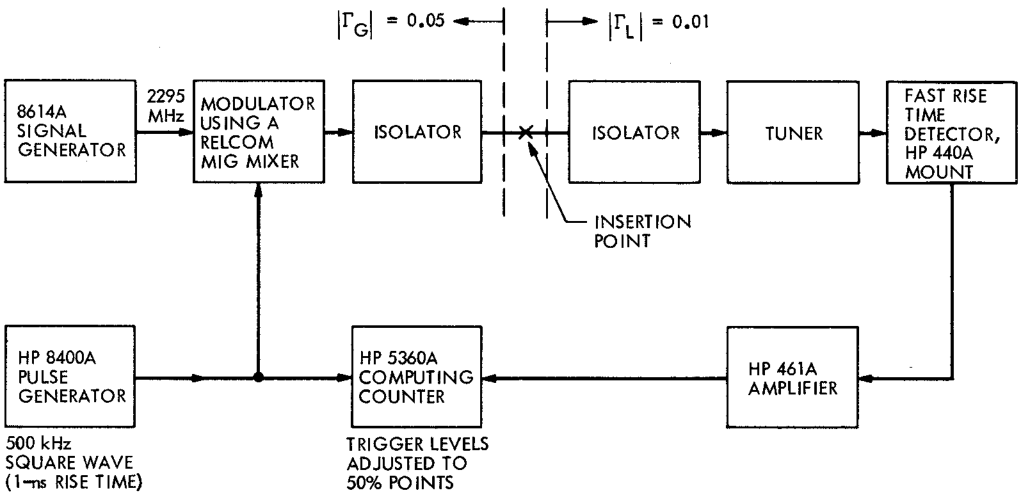

Fig. 2. Block diagram of delay measurement method utilizing a computer counter

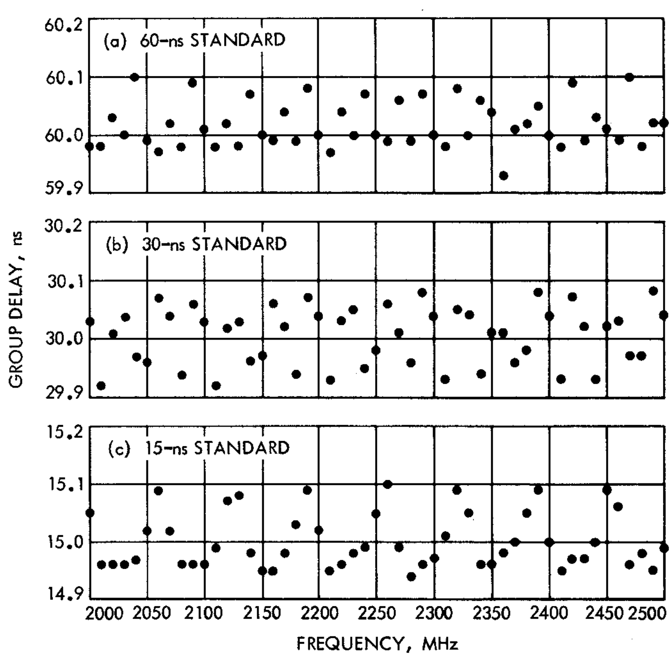

Fig. 3. Measured group delays of 15, 30, and 60 ns standards in the frequency range of 2000 to 2500 MHz (frequency interval associated with each data point was 20 MHz)

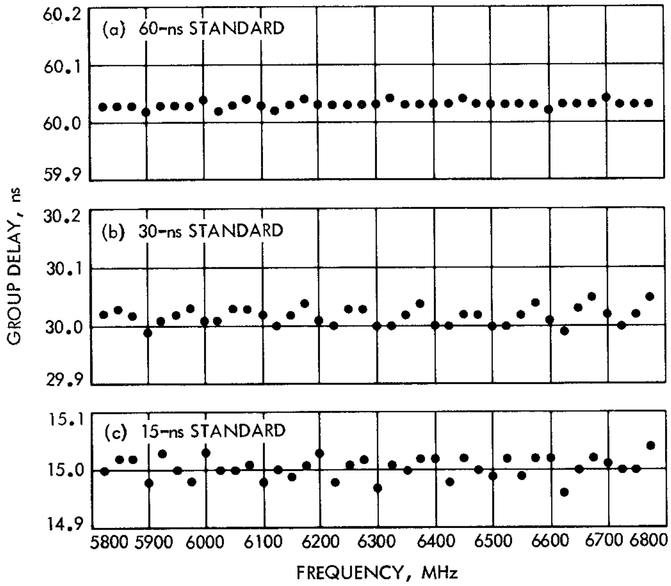

Fig. 4. Measured group delays of 15, 30, and 60 ns standards in the frequency range of 5775 to 6775 MHz (frequency interval associated with each data point was 50 MHz)

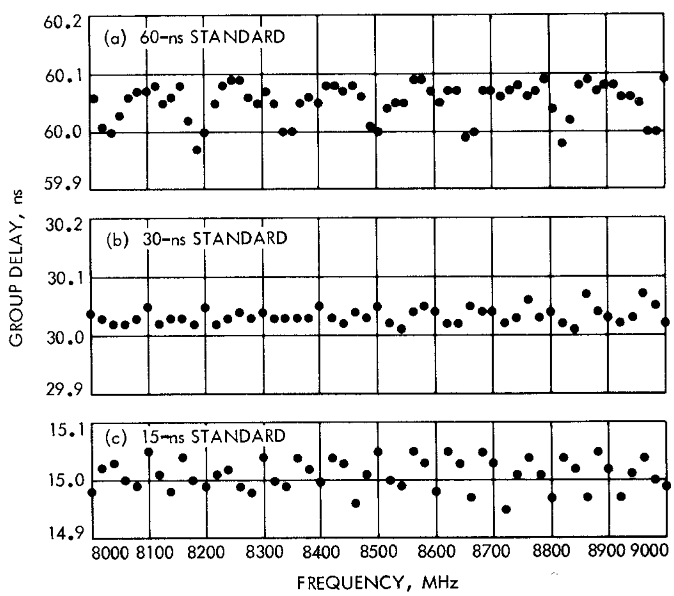

Fig. 5. Measured group delays of 15, 30, and 60 ns standards in the frequency range of 8000 to 9000 MHz (frequency interval associated with each data point was 40 MHz for 15 and 30 ns cables and 30 MHz for the 60 ns cable)

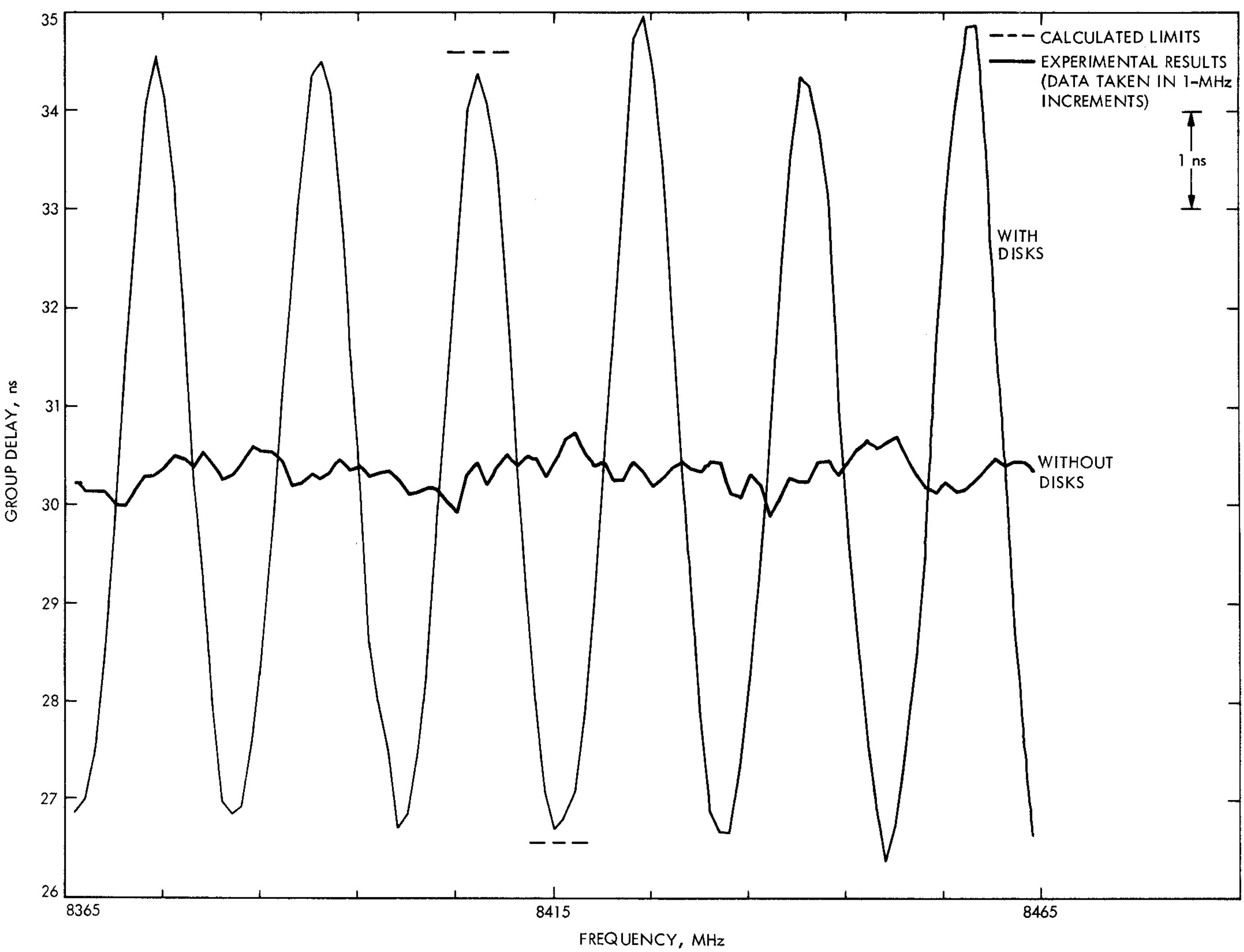

Fig. 6. Measured group delay of a 30-ns standard transmission line plus short end sections of 7-mm lines with and without 6.12-mm (0.241 in.) diam disks